GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L03105, doi:10.1029/2011GL050452, 2012

Detection of exospheric O_2^+ at Saturn's moon Dione

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Received 23 November 2011; revised 9 January 2012; accepted 10 January 2012; published 9 February 2012.

[1] During a close pass of Cassini through the plasma wake of Saturn's moon Dione on April 7, 2010 the Cassini Plasma Spectrometer (CAPS) detected molecular oxygen ions (O_2^+) on pick up ring velocity distributions, thus providing the first in situ detection of a neutral exosphere surrounding the icy moon. The density of O_2^+ determined from the CAPS data ranges from 0.01 to 0.09 /cm^3 and is used to estimate the exosphere O_2 radial column density, obtaining the range 0.9 to 7 × 10^{11}/cm^2 . CAPS was unable to directly detect pick up H_2O^+ from the exosphere but the observations can be used to set an upper limit to their density of ∼10 times the O_2^+ density. **Citation:** Tokar, R. L., R. E. Johnson, M. F. Thomsen, E. C. Sittler, A. J. Coates, R. J. Wilson, F. J. Crary, D. T. Young, and G. H. Jones (2012), Detection of exospheric O_2^+ at Saturn's moon Dione, *Geophys. Res. Lett.*, *39*, L03105, doi:10.1029/2011GL050452.

1. Introduction

[2] Saturn's moon Dione (radius ∼560 km) is in an approximately circular orbit at a radial distance from Saturn of about 6.3 Saturn radii (R_S = 60,268 km), outside the orbits of Enceladus (R = 3.9 R_S) and Tethys (R = 4.9 R_S) and inside Rhea (R = 8.7 R_S). Dione is one of Saturn's icy moons, with a surface dominated by water ice [*Fink et al.*, 1976]. It's orbital speed is about 10 km/s, so that the proton and water group (O^+, OH^+, H_2O^+, and H_3O^+) plasma in Saturn's inner magnetosphere, with speed comparable to the rigid corotation speed at Dione's orbit (∼62 km/s), overtakes the moon. This plasma impacts and is absorbed by Dione's surface creating a plasma void region (a wake) extended in the direction of Dione's orbital velocity and possibly a neutral exosphere via radiolysis and sputtering. To date there have been two flybys of Dione by Cassini, on Oct 11, 2005 an upstream flyby (D1) and on April 7, 2010 a wake flyby (D2), both at altitudes of about 500 km. In this study, the in situ detection of O_2^+ pick-up ions by the Cassini plasma spectrometer (CAPS) [*Young et al.*, 2004] during D2 is reported. (No similar pick-up was detected by CAPS during the D1 flyby due to the unfavorable upstream geometry.) The pick-up ions are produced when neutrals in the exosphere are ionized primarily via charge exchange, with electron impact and photo ionization also contributing. The newly produced pick-up ions are swept downstream in Saturn's magnetic field. The observations confirm the existence of a sputter-produced neutral exosphere at Dione with associated mass-loading and are consistent with CAPS observations of enhanced plasma production near Dione's orbit [*Tokar et al.*, 2008]. In addition, recent magnetohydrodynamic modeling of the D1 magnetic field signature measured during D1 suggested the presence of a neutral exosphere [*Simon et al.*, 2011], albeit one with much higher density than that inferred here.

[3] During the Pioneer and Voyager Saturn flybys, all far from Dione, unexplained correlations of Saturn's plasma properties, kilometric radiation, and ion cyclotron emission with Dione's orbital distance and period were noted [*Frank et al.*, 1980; *Kurth et al.*, 1981; *Smith and Tsurutani*, 1983; *Barbosa*, 1993]. In 1997, using the Hubble Space Telescope, *Noll et al.* [1997] reported the detection of ozone (O_3) in Dione's surface water ice, indicating concentrations of trapped molecular oxygen (O_2). The O_2 and O_3 are thought to be produced primarily by surface radiolysis, a process [e.g., see *Johnson and Sittler*, 1990] recently identified by Cassini at the moon Rhea [*Teolis et al.*, 2010]. In preparation for the Cassini mission, *Sittler et al.* [2004] modeled a possible sputter-produced exosphere at Dione and suggested the existence of an exosphere could be inferred by CAPS via detection of pick-up ions during wake flybys, a prediction confirmed in this paper. Following Sittler et al., *Saur and Strobel* [2005] also modeled a possible exosphere at Dione and the strength of Dione's interaction with the magnetospheric plasma, predicting the associated mass-loading. More recently, *Johnson et al.* [2008] used the average CAPS plasma data to calculate new sputtering rates for the icy satellites that included the temperature dependent contribution from radiolytic decomposition of ice resulting in the production of O_2.

2. Cassini Plasma Spectrometer Observations

[4] Figures 1 and 2 illustrate the Cassini trajectory and CAPS ion measurements during the Dione 2 encounter, with Figure 3 illustrating the CAPS electron observations. In the Dione frame of reference a coordinate system is defined with +x in the direction of nominal plasma corotation, +y toward Saturn, and the z axis completing a right-handed system. Referring to Figure 1 (top), Cassini moves from left to right (at 8.4 km/s with respect to Dione) with position in the x-y plane shown as the blue line. The approximately corotating plasma in Saturn's magnetosphere flows from the bottom to the top in the +x direction, creating the geometric wake. The z coordinate of Cassini is approximately zero throughout the encounter, as shown in the z-y trajectory in Figure 2 (top).

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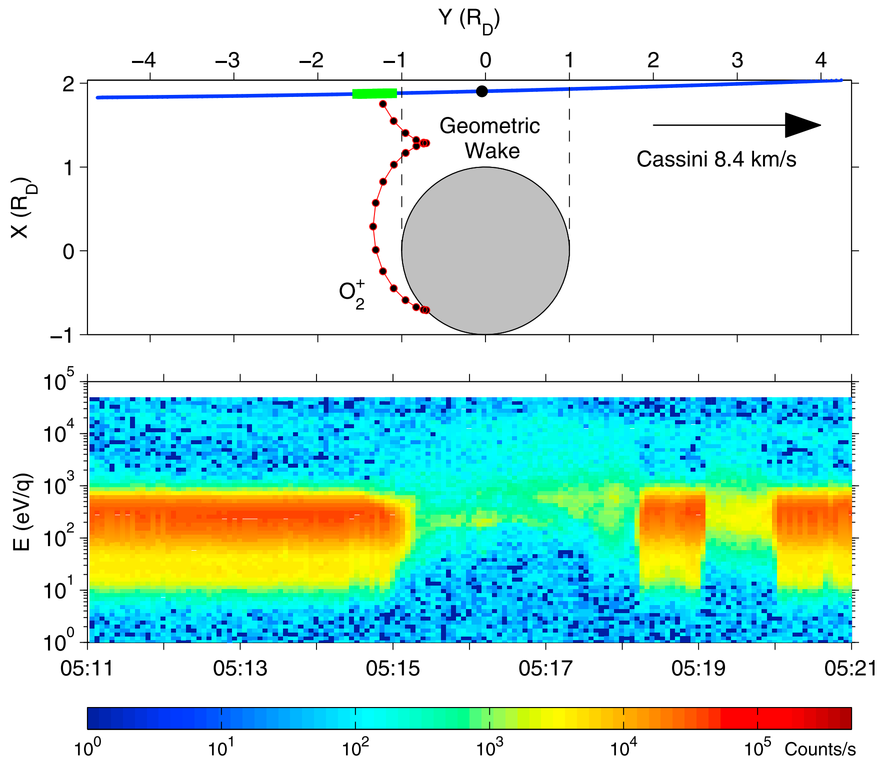

Figure 1. (bottom) CAPS ion count rate at 4s resolution as a function of time and energy per charge. The measurements are for anode 4 of CAPS, sensing flow predominantly in the corotation direction. (top) Cassini trajectory during D2 and Dione's geometric wake, with a sample pick-up O_2^+ ion trajectory in the ambient flow plotted at 2s resolution. The pick up ions are detected by CAPS just before entering the wake, in the green shaded region on the trajectory.

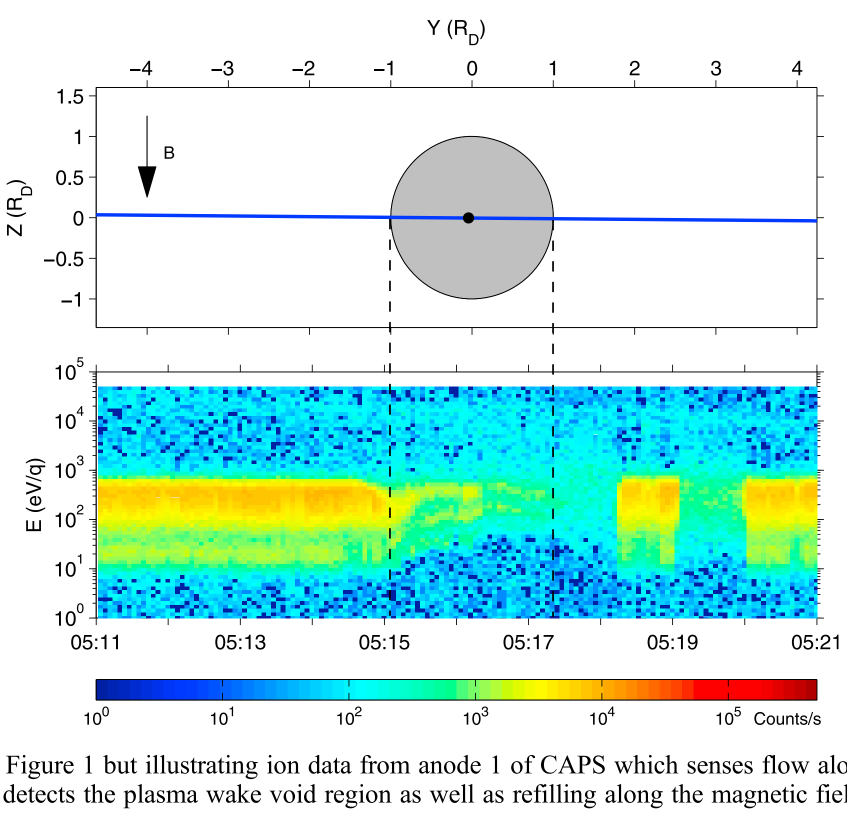

Figure 2. Similar to Figure 1 but illustrating ion data from anode 1 of CAPS which senses flow along the magnetic field direction. This anode detects the plasma wake void region as well as refilling along the magnetic field.

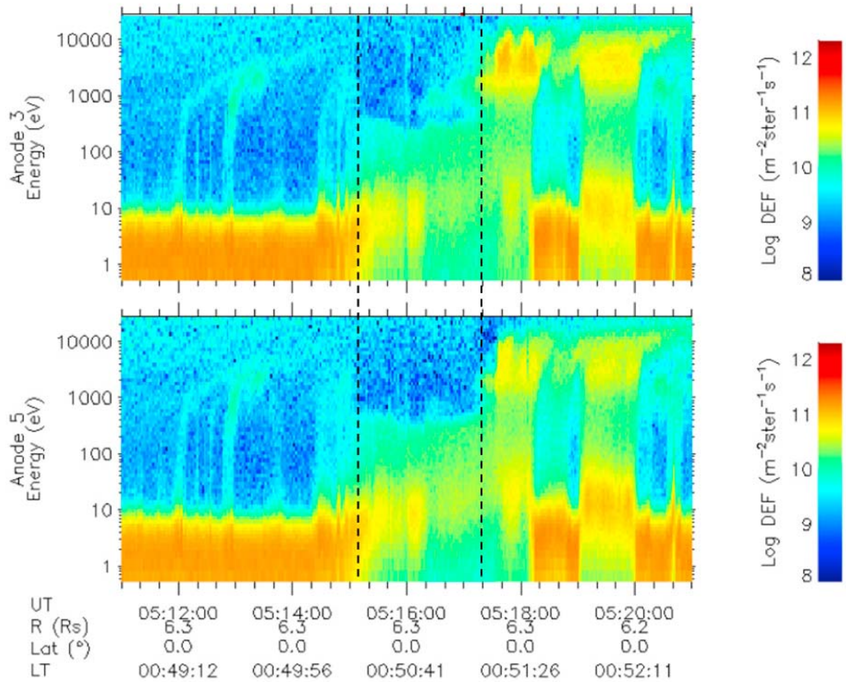

Figure 3. CAPS electron spectrometer observations during the D2 encounter. See text for details.

Therefore, during the Dione 2 encounter Cassini passes directly through the wake void region and near the equatorial plane, with closest approach to Dione at 05:16:11.

[5] The CAPS ion observations are discussed first, followed by the electron observations. During the encounter the 8 detectors of the CAPS ion mass spectrometer (IMS) were at a fixed look direction, sampling different ion pitch angles. Typically the CAPS actuator [*Young et al.*, 2004] is held fixed during the relatively fast moon encounters with CAPS anodes each sampling different ion gyro plane phases or pitch angles. In Figure 1 (bottom), measurements from IMS anode 4 are shown, which during D2 sensed ion flow approximately in the +x corotation direction. Similarly, Figure 2 (bottom) illustrates measurements from IMS anode 1 which detected ions flowing southward (-z) along the magnetic field direction during this encounter. The color-coded ion count rate for both anodes is plotted as a function of time (4s resolution) over the energy per charge range of about 1 eV to 46 keV. Before the encounter, from about 05:11:00 to at least 05:14:00 UT, Figures 1 (bottom) and 2 (bottom) illustrate typical thermal plasma, consisting of H^+, H_2^+ and water group ions, nearly corotating at these radial distances. CAPS thermal plasma moments yield an ion flow speed in the azimuthal corotation direction with value 39 $\pm$ 6 km/s with respect to Dione, or $\sim$79% of perfect corotation. Note that because CAPS is not actuating no information is available on the radial flow velocity during the encounter. Within the geometric wake both ion detector count rates are small, indicative of a plasma void region. Ion acceleration into the wake from the northern wake boundary is evident in the anode 1 data (Figure 2) with a typical signature of ambipolar diffusion [e.g., see *Samir et al.*, 1983]. At later times after leaving the wake the ion data show the characteristic signature of ion injection events [e.g., *Hill et al.*, 2005] leading to a complex plasma environment.

[6] Figure 3 illustrates electron measurements from the CAPS electron spectrometer (ELS) during the encounter, with anode 5 in the bottom panel illustrating the usual low energy plasma population in Saturn's dynamic magnetosphere at this distance (<10 eV). This plasma is disturbed by plasma wake effects at Dione (05:14:40–05:18:20), and also, throughout the interval, by superimposed injection events [*Hill et al.*, 2005]. The injection events are present both before closest approach (e.g., 05:12 and 05:12:50) and afterwards (e.g., an extended event 05:19–05:20, and an extended event which appears to be superposed on the wake signature itself between 05:17:40–05:18:00). The events before closest approach resemble remote injections while at later times they resemble local injections [*Burch et al.*, 2005; *Hill et al.*, 2005; *Rymer et al.*, 2009]. The wake signature as seen by ELS consists of a population depleted in flux, but rising in energy to $\sim$30 eV, as well as a population which persists for the whole wake period (05:14:40–05:18:20) with a maximum energy $\sim$400 eV. Electron pitch angle data (not shown) reveal a refilling of the plasma wake behind Dione by electrons with up to a few hundred eV. Clearly, the ELS signature indicates a complex combination of wake effects and dynamic magnetospheric effects including injection events. In addition, data from anode 3 (Figure 3, top) show a remarkably narrow (in energy) and long-lived feature in the wake region between $\sim$05:15:30 and 05:17, which has an energy of $\sim$600 eV, intensifies with time, increases a little in energy and eventually apparently merges with an injection signature. It is possible that this feature corresponds to negative pickup ions as observed at Rhea [*Teolis et al.*, 2010], complementary with the positive pickup ions we report before closest approach, but further analysis is required to confirm this. In particular it is difficult to rule out the role of injection events in producing this population, which will be the subject of a separate study.

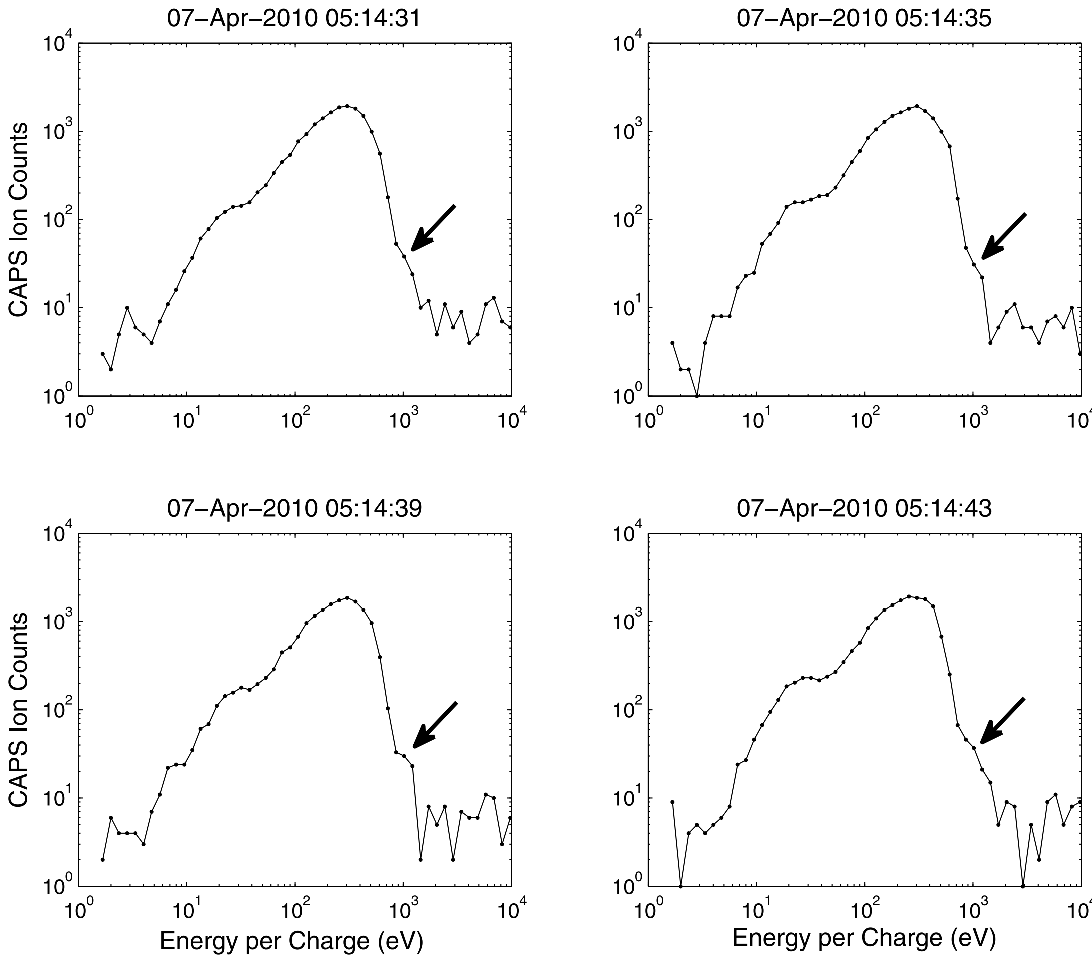

Figure 4. CAPS anode 4 spectra separated by 4s and just outside the wake. Arrows point out the bump in counts attributed to the freshly produced pick up ions. This figure illustrates that the pick-up ion signature attributed to O_2^+ persists over multiple CAPS spectra for at least 32s.

[7] Of primary importance here are the ion measurements from IMS anode 4 just before and while entering the geometric wake region (Figure 1). Recall this anode is sensing flow predominantly in the corotation direction perpendicular to the magnetic field. It is expected that a newly born ion out of a Dione exosphere will be picked up by Saturn's magnetic field and swept away, with a typical trajectory shown by the red curve in Figure 1 (top). This trajectory is plotted at 2s intervals for an O_2^+ ion picked up into a bulk flow along +x of 39 km/s (with respect to Dione) and a uniform magnetic field of 75 nT in the −z direction [*Khurana et al.*, 2008]. Because this is a low altitude wake pass, freshly produced ions are most likely on a ring velocity space distribution [*Sittler et al.*, 2004] and CAPS anode 4, viewing mainly perpendicular to the magnetic field direction, should detect them as a "bump" in the count rate at energies greater than the main water group ions. (It is also possible that the ions could be non gyrotropic "streams", although CAPS has no measurements at various ion gyrophases.) As illustrated in Figure 4, such a signature is observed by CAPS in four slices of IMS ion counting data versus energy per charge measured in the region just before entering the wake void (green shaded region on the Cassini trajectory, Figure 1, top). The arrows in Figure 4 point out the bump in the spectra, attributed here to the presence of freshly-produced pick-up ions.

[8] Figure 5 expands on the results in Figure 4, showing in Figure 5 (top) average CAPS IMS ion counts versus energy for anode 4 at early times well away from Dione (05:11:15 to 05:11:27 UT, see Figure 1) and in Figure 5 (bottom), the average of the 4 spectra in Figure 4. In Figure 5 (top) the green curve is a fit to the water group core using a Maxwellian velocity distribution. Note the high energy tail (produced by hot H^+ and W^+ , determined by CAPS time of flight data not shown here) between about 1 and a few keV. It is, not surprisingly, not well fit by the Maxwellian but is not a "bump" like those seen in Figure 4. For the average spectrum (Figure 5, bottom) fits are shown consisting of H^+ (red dashed), H_2^+ (red), W^+ (green), and the sum (blue) is shown. Also illustrated are the nominal positions in energy of H_2O^+ and O_2^+ ring distributions for the average core flow speed of 39 km/s. From the *Sittler et al.* [2004] study, the dominant freshly-produced ion from a Dione exosphere would be H_2O^+, with minor ions also created including O_2^+. The conclusion from this result is that the bump measured at higher energies is most likely O_2^+ pick-up ions and that H_2O^+ pick-up ions if present would be difficult to observe within the high count water group core. This result holds over the azimuthal flow speed range measured by CAPS near Dione of 39 ± 6 km/s (in the Dione frame). For this range of speeds, a relatively cold O_2^+ ring, expected for new pick-up ions, has a midpoint energy

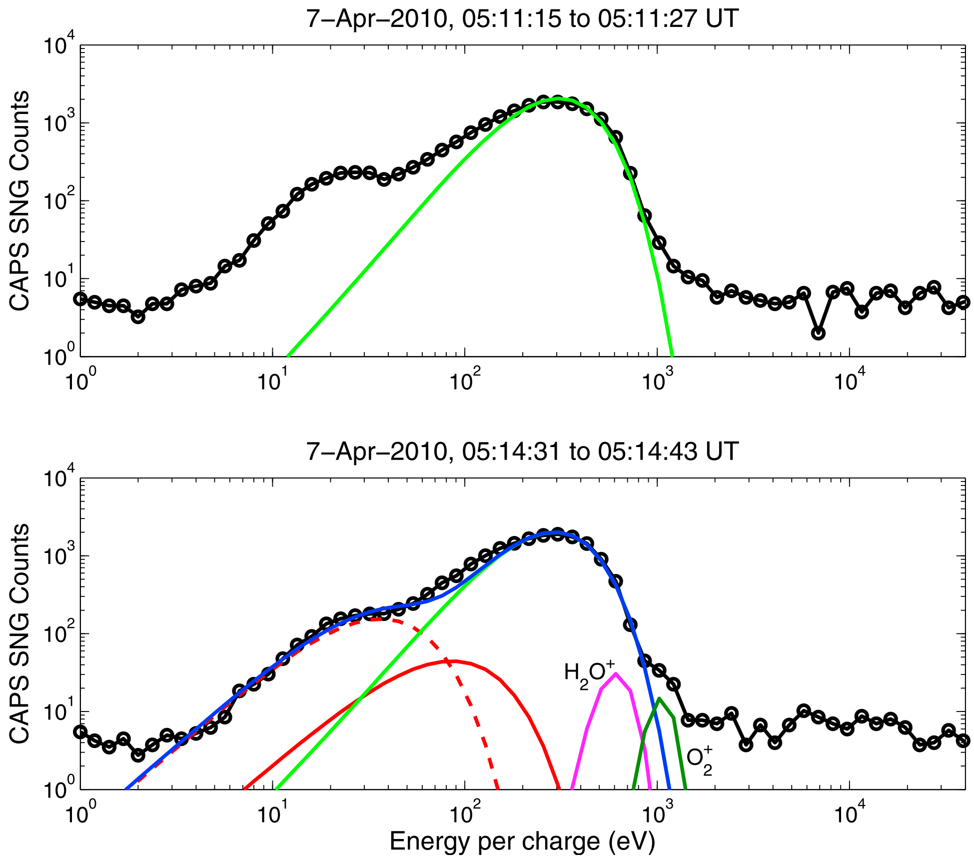

Figure 5. This figure shows CAPS average ion counts measured by anode 4 (black circles) (top) far from Dione and (bottom) close to the moon's wake. In addition, ion counts are simulated for both O_2^+ and H_2O^+ pick-up ion rings for the nominal plasma flow, indicating good agreement of the observed pick-up ion energy with the simulated O_2^+ pick-up ion energy.

near the CAPS 1.02 keV energy channel with a range for these flow speeds of 724 eV to 1.45 keV. On the other hand, cold pick-up H_2O^+ has the midpoint energy near the 609 eV channel, as shown in Figure 5, with a range from 430 to 725 eV, well below the energies measured for the bump. These results are a strong indication that the bumps in the CAPS spectra are due to O_2^+ pick up ions.

3. Discussion

[9] The CAPS ion counts at the O_2^+ ring energy (Figures 4 and 5) can be used to provide a rough estimate of the O_2^+ pick-up ion density. This result can in turn be used to test the modeling of the proposed O_2 atmosphere. Our pick-up ion density estimate is rough primarily because of the large uncertainty in the velocity space distribution of these ions. The estimate is calculated for uniform ring and shell velocity space distributions and the temperature for both is chosen as 10 eV, reasonable given the energy spread of the bump shown in Figure 5. For the estimate of O_2^+ density, the measured CAPS counts at 1.02 keV, corrected for background, are attributed entirely to O_2^+ and used to calculate a representative phase space density for this ion. Assuming uniform density, this is multiplied by the volume of velocity space for a ring or shell to obtain number density. The phase space density is $f_i = C/(v^4 G \varepsilon \Delta t)$, with C the ion counts at the peak of the bump (1.02 keV) corrected for background, v the speed of an O_2^+ ion with energy 1.02 keV, $G = 7.44 \times 10^{-4}$ cm^2, the CAPS geometric factor at this energy, $\varepsilon = 0.46$, the detection efficiency for O_2^+, and $\Delta t = 54.7$ ms, the sample time. The volume of the ring in velocity space is $V = (2\pi V_{ring})(\pi v_{th}^2)$ where $V_{ring} = 39$ km/s is the ring radius and v_{th} is the thermal speed of the ring O_2^+ ions assuming T = 10 eV. A similar expression is used for the volume of a shell. The results of this are summarized in Table 1, with the density of O_2^+ ranging from 0.01 ± 0.001 cm^{-3} for a ring and

Table 1. Summary of Analysis of CAPS Pick-Up Ion Counts to Extract O_2^+ Density for the Four Ion Energy Spectra Shown in Figure 4[a]

Time (UT)	Counts (1.02 keV)	Background (10 to 46 keV)	O_2^+, f (s^3/cm^6)	O_2^+, N (ring) (cm^{-3})	O_2^+, N (shell) (cm^{-3})
05:14:31	38	6.0	4.7×10^{-22}	0.011	0.099
05:14:35	31	4.6	3.9×10^{-22}	0.009	0.082
05:14:39	30	5.2	3.5×10^{-22}	0.008	0.074
05:14:43	37	5.7	4.6×10^{-22}	0.011	0.097

[a]The fourth column is ion phase space density for the peak of the ion bump assuming these counts are solely due to O_2^+. The last two columns give the resulting ion density for ring and shell velocity space distributions.

0.09 ± 0.01 cm^3 for a shell. The result for the ring is the most probable of these two, given the close proximity of Cassini to the source region (see Figure 1) and that the ring may only be partially filled, i.e., non-gyrotropic or streams of ions, as observed by CAPS at Rhea [*Teolis et al.*, 2010]. As for the possible presence of H_2O^+ pick-up, the CAPS results can be used to estimate an upper limit density by calculating the H_2O^+ density needed to produce 100 counts in CAPS IMS. This level of counts is a rough threshold above which the ring distribution would be observable within the high count W^+ core. This calculation yields an upper limit density of H_2O^+ pick up ions about 5 to 10 times higher than that for O_2^+ on either ring or shell velocity distributions.

[10] In anticipation of Cassini encounters with Dione, *Sittler et al.* [2004] estimated pick-up ion densities near Dione, in particular expectations for a wake pass like D2. Using estimates of the plasma properties at Saturn from Voyager, they obtained pick-up densities $\sim$0.07 O_2^+/cm^3 and $\sim$0.8 H_2O^+/cm^3 for the D2 geometry, remarkably consistent with the estimates presented here. Their results were calculated using a net sputter flux of 9.6×10^{25} H_2O/s with a source rate for O_2 that was 10% of the H_2O source rate. That estimate, based on the assumption of a significant sputtering contribution from energetic O^+, is fortuitously close to a recent estimate based on the CAPS thermal plasma data [*Johnson et al.*, 2008]. The corresponding source rate of O_2 from plasma induced decomposition of ice, which is sensitive to the surface temperature, is also close to the assumed 10% of the H_2O source rate. (Assuming a mean surface temperature $\sim$87 K, and using the activation energy of *Johnson et al.* [2008], the result is $\sim$7%.) The ionization rate used is also reasonably close to the Voyager estimate but the description of their atmosphere was simplified as the ejected O_2 has an escape fraction, $f_S \sim 0.36$ for the assumed ejecta speed distribution for O_2. Therefore, most O_2 returns to the surface, is transiently absorbed, and is re-emitted thermally accommodated to the average surface temperature as discussed earlier for Rhea [*Teolis et al.*, 2010] and Europa [*Johnson et al.*, 2009]. Therefore, the O_2 that does not escape accumulates until the loss rate, due to escape, ionization and dissociation, equals the source rate. Noting that the ballistic lifetime for O_2 is $\sim$2000 sec whereas the lifetimes against ionization and dissociation are $\sim 10^6$–10^7 s, the oxygen is cycled through the atmosphere many times prior to its destruction.

[11] The dependence of the density, n, vs. radial distance, r, of this ballistic thermal atmosphere using a mean surface temperature of 87 K with Jeans parameter (gravitational escape energy/ kT) $\sim$5.6, is also quite close to that in Figure 1a of *Sittler et al.* [2004]. Because the accumulation of pick-up ions along the fluid element is dominated by pick-up where the neutral density is largest (i.e., when the element is closest to Dione's surface), we can use the ratio between the calculated pick-up ion density, $\sim$0.07/cm^3 and the neutral density at the surface, $n_o \sim 2 \times 10^4$/cm^3. However, the calculated pick-up ion density for the model atmosphere was estimated assuming a small gyroradius: i.e., treating the ions motion as a fluid. In a recent paper, *Hartle and Sittler* [2007] accounted for the ratio of the ion gyroradius, $\sim$180 km, to the scale height, $\sim$100 km, to correct the pick-up ion density estimates. Using Figure 6 of *Hartle and Sittler* [2007] the density would be a factor of $\sim$1/2 smaller. Therefore, we scale our results using $2(2 \times 10^4/0.07) \sim 6 \times 10^5$ for the ratio of surface O_2 density to O_2^+ pick-up ion density for a Cassini wake pass. Based on our range of pick-up ion densities (0.01–0.09 O_2^+/cm^3) and assuming the same total ionization rate ($\sim 2 \times 10^{-7}$/s), Dione's O_2 atmosphere has a surface density in the range $n_o \sim 0.6$–5×10^4/cm^3. This would be a rough lower bound if the fluid elements detected did not sample down to the physical surface. Using these densities, a rough estimate of the O_2 radial column density ~ 0.9–7×10^{11}/cm^2 , is of the order of that found at Rhea [*Teolis et al.*, 2010] but much smaller than the recent estimate for Dione using D1 magnetometer data [*Simon et al.*, 2011].

[12] There are uncertainties in this calculation, not only in the density of the O_2^+ pick-up ions but also the location and structure of the detected fluid elements and the fact that the local ionization rates can differ from that in the background gas. More importantly, the surface temperature is not uniform with significant day-night and equator-pole differences ranging from $\sim$50–90 K [*Howett et al.*, 2010]. This affects the production, escape, redistribution and, possibly, the burial of O_2 across the surface, allowing for the possibility of build up in the regolith in the colder regions. The radiation chemistry involved has been reviewed recently [*Johnson*, 2011]. These issues will be dealt with in subsequent, more detailed modeling. However, what is not uncertain is we report here the first in situ detection of a component of Dione's thin sputter produced atmosphere by collecting the pick-up ions. Since the pick-up ion density is directly related to the atmospheric densities, we have also obtained a rough estimate of the atmospheric O_2 density. This is consistent with the earlier observations of oxygen products trapped in the surface ice and places Dione in a category with Europa, Ganymede, Rhea and Saturn's main rings all of which have oxygen atmospheres.

[13] **Acknowledgments.** The authors wish to thank Krishan Khurana for helpful conversations regarding the Cassini Dione observations. The work of U.S. co-authors was supported by JPL contracts 1243218 with Southwest Research Institute. We acknowledge support of the CAPS ELS operations and software team by the UK Science and Technology Facilities Council (STFC, to 2010) and by ESA via UK Space Agency (from 2011), and support of CAPS-ELS science by STFC. GHJ is supported by an STFC Advanced Fellowship. Cassini is managed by the Jet Propulsion Laboratory for NASA.

[14] The Editor thanks Ying-Dong Jia and an anonymous reviewer for their assistance in evaluating this paper.

References

Barbosa, D. D. (1993), Theory and observations of electromagnetic ion cyclotron waves in Saturn's inner magnetosphere, *J. Geophys. Res.*, *98*(A6), 9345–9350, doi:10.1029/93JA00476.

Burch, J. L., J. Goldstein, T. W. Hill, D. T. Young, F. J. Crary, A. J. Coates, N. André, W. S. Kurth, and E. C. Sittler Jr. (2005), Properties of local plasma injections in Saturn's magnetosphere, *Geophys. Res. Lett.*, *32*, L14S02, doi:10.1029/2005GL022611.

Fink, U., et al. (1976), Infrared spectra of the satellites of Saturn: Identification of water ice on Iapetus, Rhea, Dione, and Tethys, *Astrophys. J.*, *207*, L63–L67, doi:10.1086/182180.

Frank, L. A., B. G. Burek, K. L. Ackerson, J. H. Wolfe, and J. D. Mihalov (1980), Plasmas in Saturn's magnetosphere, *J. Geophys. Res.*, *85*(A11), 5695–5708, doi:10.1029/JA085iA11p05695.

Hartle, R. E., and E. C. Sittler Jr. (2007), Pickup ion phase space distributions: Effects of atmospheric spatial gradients, *J. Geophys. Res.*, *112*, A07104, doi:10.1029/2006JA012157.

Hill, T. W., A. M. Rymer, J. L. Burch, F. J. Crary, D. T. Young, M. F. Thomsen, D. Delapp, N. André, A. J. Coates, and G. R. Lewis (2005), Evidence for rotationally driven plasma transport in Saturn's magnetosphere, *Geophys. Res. Lett.*, *32*, L14S10, doi:10.1029/2005GL022620.

Howett, C. J. A., et al. (2010), Thermal inertia and bolometric Bond albedo values for Mimas, Enceladus, Tethys, Dione, Rhea and Iapetus as derived from Cassini/CIRS measurements, *Icarus*, *206*, 573–593, doi:10.1016/j.icarus.2009.07.016.

Johnson, R. E. (2011), Photolysis and radiolysis of water ice, in *Physics and Chemistry at Low Temperatures*, edited by L. Khriachtchev, chap. 10, pp. 297–339, World Sci., Singapore.

Johnson, R. E., and E. C. Sittler Jr. (1990), Sputter-produced plasma as a measure of satellite surface composition: The CASSINI mission, *Geophys. Res. Lett.*, *17*(10), 1629–1632, doi:10.1029/GL017i010p01629.

Johnson, R. E., et al. (2008), Sputtering of ice grains and icy satellites in Saturn's inner magnetosphere, *Planet. Space Sci.*, *56*, 1238–1243, doi:10.1016/j.pss.2008.04.003.

Johnson, R. E., et al. (2009), Composition and detection of Europa's sputter-induced atmosphere, in *Europa*, edited by R. Pappalardo et al., pp. 507–527, Univ. of Ariz., Tucson.

Khurana, K. K., C. T. Russell, and M. K. Dougherty (2008), Magnetic portraits of Tethys and Rhea, *Icarus*, *193*, 465–474, doi:10.1016/j.icarus.2007.08.005.

Kurth, W. S., D. A. Gurnett, and F. L. Scarf (1981), Control of Saturn's kilometric radiation by Dione, *Nature*, *292*, 742–745, doi:10.1038/292742a0.

Noll, K. S., et al. (1997), Detection of ozone on Saturn's satellites Rhea and Dione, *Nature*, *388*, 45–47, doi:10.1038/40348.

Rymer, A. M., et al. (2009), Cassini evidence for rapid interchange transport at Saturn, *Planet. Space Sci.*, *57*, 1779–1784, doi:10.1016/j.pss.2009.04.010.

Samir, U., K. H. Wright Jr., and N. H. Stone (1983), The expansion of a plasma into a vacuum: Basic phenomena and processes and applications to space plasma physics, *Rev. Geophys.*, *21*(7), 1631–1646, doi:10.1029/RG021i007p01631.

Saur, J., and D. F. Strobel (2005), Atmospheres and plasma interactions at Saturn's largest inner icy satellites, *Astrophys. J.*, *620*, L115–L118, doi:10.1086/428665.

Simon, S., J. Saur, F. M. Neubauer, A. Wennmacher, and M. K. Dougherty (2011), Magnetic signatures of a tenuous atmosphere at Dione, *Geophys. Res. Lett.*, *38*, L15102, doi:10.1029/2011GL048454.

Sittler, E. C., R. E. Johnson, S. Jurac, J. D. Richardson, M. McGrath, F. Crary, D. T. Young, and J. E. Nordholt (2004), Pickup ions at Dione and Enceladus: Cassini plasma spectrometer simulations, *J. Geophys. Res.*, *109*, A01214, doi:10.1029/2002JA009647.

Smith, E. J., and B. T. Tsurutani (1983), Saturn's magnetosphere: Observations of ion cyclotron waves near the Dione *L* shell, *J. Geophys. Res.*, *88*(A10), 7831–7836, doi:10.1029/JA088iA10p07831.

Teolis, B. D., et al. (2010), Cassini finds an oxygen-carbon dioxide atmosphere at Saturn's icy moon Rhea, *Science*, *330*, 1813–1815, doi:10.1126/science.1198366.

Tokar, R. L., et al. (2008), Cassini detection of water-group pick-up ions in the Enceladus torus, *Geophys. Res. Lett.*, *35*, L14202, doi:10.1029/2008GL034749.

Young, D. T., et al. (2004), Cassini plasma spectrometer investigation, *Space Sci. Rev.*, *114*, 1–112, doi:10.1007/s11214-004-1406-4.

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